Transport study of charged current interactions in neutrino-nucleus reactions

W. Cassing [a,*] M. Kant [a] K. Langanke [b] P. Vogel [c]

[a] *Institut für Theoretische Physik, Universität Giessen, Heinrich–Buff–Ring 16, D–35392 Giessen, Germany*

[b] *GSI Darmstadt, Planckstr. 1, D–64220 Darmstadt, Germany*

[c] *California Institute of Technology, Kellogg. Lab. 106-38, Pasadena, CA 91125, USA*

Abstract

Within a dynamical transport approach we investigate charged current interactions in neutrino-nucleus reactions for neutrino energies of 0.3 - 1.5 GeV with particular emphasis on resonant pion production channels via the $\Delta_{33}(1232)$ resonance. The final-state-interactions of the resonance as well as of the emitted pions are calculated explicitly for ^{12}C and ^{56}Fe nuclei and show a dominance of pion suppression at momenta $p_\pi > 0.2$ GeV/c. A comparison to integrated π^+ spectra for $\nu_\mu+^{12}C$ reactions with the available (preliminary) data demonstrates a reasonable agreement.

Key words: Neutrino interactions, Models of weak interaction, Axial vector currents
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1 Introduction

The interest in neutrino induced reactions has been rapidly increasing during the last decade while current and future long base-line (LBL) experiments, K2K, Mini-Boone, MINOS, CERN-GS, J2K *etc.* aim at determining the electro-weak response of nucleons and nuclei. In general the neutrino-nucleon/nucleus interaction consists of the quasi-elastic scattering, resonance production and deep inelastic scattering, the latter becoming dominant only for neutrino energies above about 1 GeV increasing further linearly with energy. Whereas at low neutrino energies $E_\nu < 0.3$ GeV the

* corresponding author
Email address: Wolfgang.Cassing@theo.physik.uni-giessen.de (W. Cassing).

quasi-elastic channel clearly dominates, one observes an increasing contribution from resonance excitations at higher energies up to about 2 GeV [1]. Here charged current (CC) reactions offer the unique possibility to measure the μ^- in coincidence with e.g. the charged $\pi^\pm$ or neutral π^0 in order to extract information on the resonance transition form factors since the 4-momentum of the lepton fixes the transferred energy ν and 4-momentum squared q^2.

A variety of models (and event generators) treat neutrino nucleus reactions [2,3,4,5,6,7,8] and incorporate selected aspects of scattering on nuclei like Pauli-blocking, nuclear Fermi motion, nucleon binding energies, pion rescattering and charge exchange reactions. However, most of the models lack an explicit propagation of the resonances and their in-medium decay to pions and nucleons as well as more realistic coordinate (and momentum) distributions of the target nucleons. In order to study the importance of these effects we employ in this work a transport approach that has been tested in a wide range of π, p reactions on nuclei as well as relativistic nucleus-nucleus collisions. For reviews we refer the reader to Refs. [9,10]. This transport model – or related versions – have been also used and tested in the description of the photo-nuclear and electron induced reactions with the momentum and energy transfer comparable to those considered here [11,12] as well as at much higher energies [13]. This is particularly relevant, since the nuclear response to electromagnetic probes is quite analogous to the weak probes addressed in this study.

For the description of the elementary process on nucleons we use the model of Rein and Sehgal [14] - with slight modifications - that has been often employed for an estimate of neutrino cross sections for resonance transitions. It is based on quark oscillator wave functions to evaluate the form factors as developed by Feynman et al. [15]. Alternatively, one may also parametrize the neutrino-nucleon-resonance vertex by introducing 'proper' vector and axial-vector form factors. The differential cross sections are well known [16] and usually given in terms of helicity amplitudes. Our present investigation is focused on final-state-interactions (FSI) of the excited $\Delta(1232)$ resonance and the emitted pion. Total π^+ cross sections from ^{12}C targets will be presented in comparison to preliminary data as a function of the neutrino energy E_ν from 0.3 to 1.5 GeV. We also provide energy differential $\pi^\pm, \pi^0$ spectra for ^{12}C and ^{56}Fe at $E_\nu = 1$ GeV and perform a differential analysis of final-state-interactions (FSI) on both targets that are used in the MiniBoone and MINOS detectors as target material. Note that alternative forms of the neutrino-nucleon-resonance vertex will modify the double differential cross sections but have no severe impact on the strength of the FSI.

2 Neutrino-nucleon reactions

We consider the interactions of a ν_μ neutrino with a nucleon that lead to a muon and pion in the final state, i.e. the charged current (CC) interactions

$$\nu_\mu + p \rightarrow \mu^- + \pi^+ + p \tag{1}$$

$$\nu_\mu + n \rightarrow \mu^- + \pi^+ + n \tag{2}$$

$$\nu_\mu + n \rightarrow \mu^- + \pi^0 + p. \tag{3}$$

Neutral current (NC) interactions are

$$\nu_\mu + p \rightarrow \nu_\mu + \pi^0 + p \tag{4}$$

$$\nu_\mu + p \rightarrow \nu_\mu + \pi^+ + n \tag{5}$$

$$\nu_\mu + n \rightarrow \nu_\mu + \pi^- + p \tag{6}$$

$$\nu_\mu + n \rightarrow \nu_\mu + \pi^0 + n. \tag{7}$$

The NC reactions with the π^0 production, eqs. (4) and (7), represent a dangerous background in the long-baseline neutrino oscillation studies, since they could be confused with the quasi-elastic electron production caused by neutrino-oscillations. We will consider the NC pion production separately in future work.

We denote the energy transfer by $\nu = E_\nu - E_l$, where E_l is the energy of the final lepton, the 4-momentum transfer squared by $q^2 = \nu^2 - Q^2 = M^2 - m_n^2 - 2m_n\nu$ with M, m_n, Q denoting the resonance mass, nucleon mass and 3-momentum transfer, respectively. We then obtain for the invariant energy (with the nucleon at rest) $W = \nu + m_n$ or alternatively $W^2 = M^2 + Q^2$. The double differential cross section for neutrino Δ-resonance excitation then reads

$$\frac{d\sigma}{dq^2 d\nu} = -\frac{(G_F \cos(\Theta_C))^2}{4\pi^2} \frac{q^2}{Q^2} \kappa \left[u^2\sigma_L + v^2\sigma_R + 2uv\sigma_s\right] \tag{8}$$

with

$$u = \frac{E_\nu + E_l + Q}{3E_\nu}, \;\; v = \frac{E_\nu + E_l - Q}{3E_\nu}, \;\; \kappa = \frac{M^2 - m_n^2}{2m_n}. \tag{9}$$

The σ terms read

$$\sigma_{L,R}(q^2, W) = \frac{WM}{\kappa m_n} \sum_{j_z} |\langle N, j_z \mp 1 | F_\mp | \Delta, j_z \rangle|^2 \; 2WA(W, M), \tag{10}$$

$$\sigma_s(q^2, W) = -\frac{W m_n}{\kappa M} \frac{Q^2}{q^2} \sum_{j_z} |\langle N, j_z \mp 1 | F_0 | \Delta, j_z \rangle|^2 \; 2W A(W, M), \tag{11}$$

where $A(W, M)$ denotes the Δ spectral function - to be specified below - which replaces the conventional term $2\pi W \delta(W^2 - M^2)$. The $N - \Delta$ transition amplitudes $F_\mp, F_0$ in (10, 11) are well known in principle [14], however, involve rather uncertain vector and axial-vector form factors which we adopt in the form

$$G^{V,A}(q^2) = \sqrt{1 - \frac{q^2}{4m_n^2}} \, \left(1 - \frac{q^2}{M_{V,A}^2}\right)^{-2} \tag{12}$$

with $M_{V,A}$ specifying characteristic mass (or inverse length) scales. We use the parameters [17] $M_V = 0.843$ GeV and $M_A = 1.032$ GeV in the following calculations (default parameter set A).

The Δ spectral function is taken in the form (with $M_\Delta = 1.232$ GeV)

$$A(W, M_\Delta) = \frac{W\Gamma(W)}{(W^2 - M_\Delta^2)^2 + W^2\Gamma^2(W)}, \tag{13}$$

where the width Γ explicitly depends on W. In vacuum a good parametrization is given by [18]

$$\Gamma(W) = \Gamma_0 \left(\frac{q}{q_r}\right)^3 \frac{M_\Delta}{W} \left(\frac{v(q)}{v(q_r)}\right)^2, \qquad v(q) = \frac{\beta^2}{\beta^2 + q^2}, \tag{14}$$

with

$$q^2(W) = (W^2 - (m_n + m_\pi)^2)(W - (m_n - m_\pi)^2)/(4W^2). \tag{15}$$

Following [18] the parameters are $\Gamma_0 = 110$ MeV, $\beta = 0.3$ GeV. Furthermore, $q_r = q(M_\Delta)$ while m_π denotes the pion mass. We have checked that alternative parametrizations only moderately change the shape of the cross section (8) in line with Ref. [19].

The results for $d\sigma/dq^2 d\nu$ for the channel $\nu_\mu + p \to \mu^- + \Delta^{++}$ are displayed in Fig. 1 for a neutrino energy $E_\nu = 1$ GeV and show a characteristic bump in the transferred energy ν due to the spectral function (13) which softens and kinematically shifts with increasing negative q^2. A similar functional dependence on ν and q^2 is known from $e^- + A$ reactions [12].

Since presently no double differential data are available for a detailed comparison and fixing of the form factors (12), we use cross sections that are integrated over ν

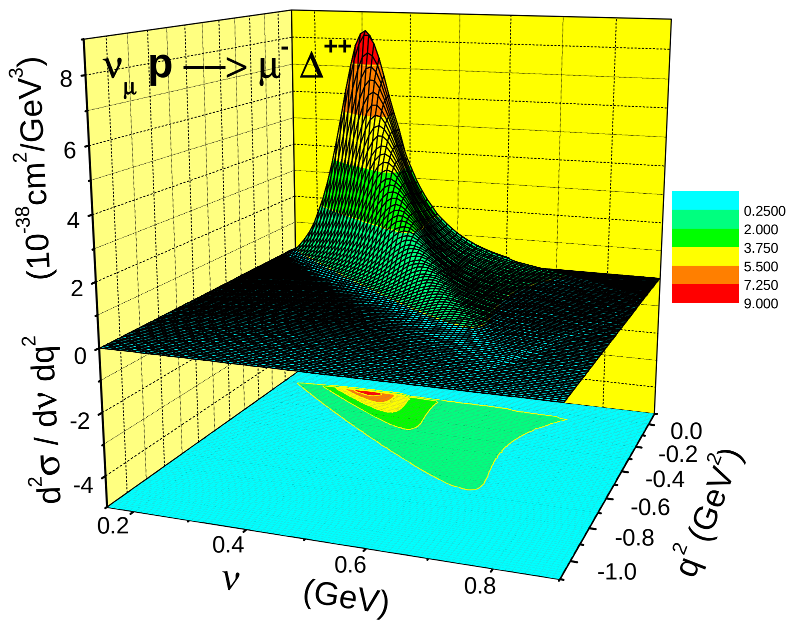

Fig. 1. The double differential cross section $d\sigma/d\nu dq^2$ for the reaction $\nu + p \to \mu^- + \Delta^{++}$ as a function of the transferred energy ν and the 4-momentum transfer squared q^2 for a neutrino energy $E_\nu = 1$ GeV.

and q^2. Note that the data in Fig. 2 [20] correspond to reactions on H_2 and D_2 and differ significantly from each other. Our standard 'historical' parameter set A [17] falls slightly low for both reactions, while calculations with a modified parameter set B ($M_V = 1$ GeV, $M_A = 1.2$ GeV) perform better (though not perfectly). Our model gives a ratio of the π^+ cross section from the proton relative to the neutron of 3 which is determined by a relative Clebsch-Gordon coefficient of $\sqrt{3}$ in the decay amplitude. The original Rein-Sehgal model [14] has an additional factor $\sqrt{3}$ in the production amplitude for the Δ^{++} relative to the Δ^+, which gives a total ratio of 1/9 for the cross sections $\nu_\mu + n \to \mu^- + \pi^+ + n$ relative to $\nu_\mu + p \to \mu^- + \pi^+ + p$. Since the data in Fig. 2 are not compatible with a ratio 1/9 but favor a ratio 1/3 we have 'redefined' the production matrix element to be identical for Δ^{++} and Δ^+. Note that also higher baryon resonances may contribute to π^+ production - especially for the $\nu_\mu + n \to \mu^- + \pi^+ + n$ channel - which are discarded in this study. These resonances have independent transition form factors that presently are not controlled by data and require further parameters. The explicit dependence of the cross section on E_ν reflects both the form factors employed as well as the detailed form of the spectral function (13).

In view of the large uncertainties in the data we do not aim at fitting the form factors here and consider instead reactions on nuclei by employing a coupled-channel transport model.

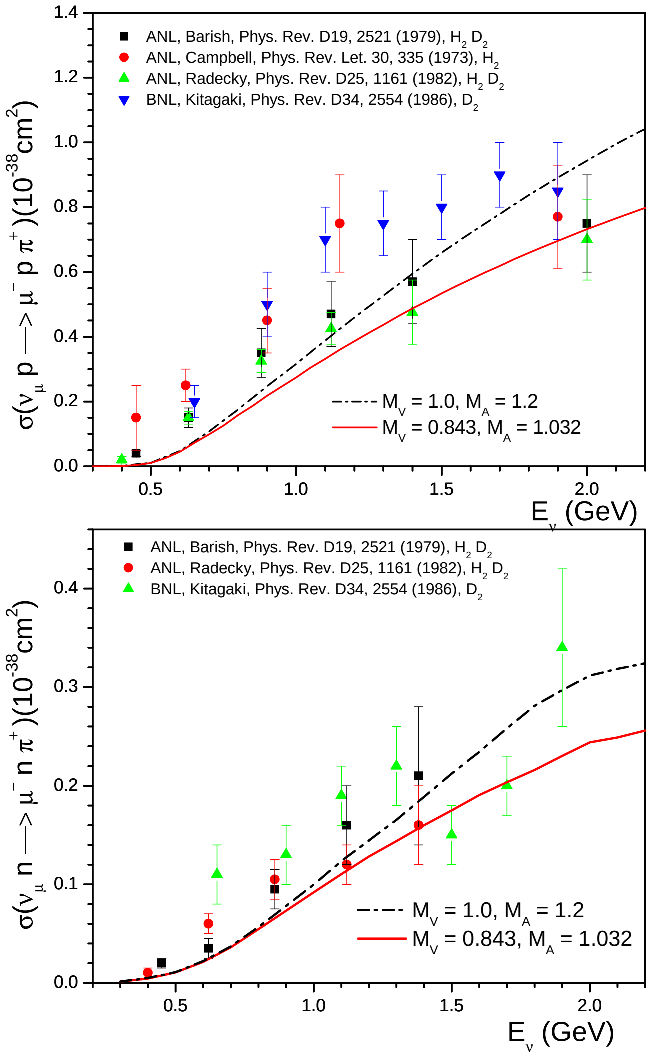

Fig. 2. The calculated cross sections for the reactions $\nu + p \to \mu^- + \pi^+ + p$ (upper part) and $\nu + n \to \mu^- + \pi^+ + n$ (lower part) as a function of the neutrino energy E_ν for the standard parameter set A ($M_V = 0.843$ GeV, $M_A = 1.032$ GeV) and the modified set B ($M_V = 1$ GeV, $M_A = 1.2$ GeV). The data are taken from Refs. [20], respectively.

3 Neutrino nucleus reactions

Relativistic transport models have been originally developed for nucleus-nucleus collisions starting from the Fermi-energy domain up to ultra-relativistic energies ($\sqrt{s} \approx$ 200 GeV) in order to extract physical information from nucleus-nucleus collisions relative to scaled proton-nucleus reactions [9,10,21,22,23,24]. These models incorporate a variety of in-medium effects such as mean-field potentials - i.e. the real part of the retarded selfenergy - as well as finite life time effects of hadrons due to multiple interactions (decays) in the medium. The latter are encoded in dynamical spectral functions for the hadrons of interest that are fully specified in terms of the real and imaginary parts of the hadron selfenergy. We recall that an off-shell transport version - suitable for the propagation of particles with finite spectral width - is available, too [25]. While the initial studies had been devoted to $A+A$ collisions, these models have been used in the description of pion-nucleus [26] and photo-nuclear reactions [11,12,27] in more recent years as well. The advantage of such transport models is that they are suited for a wide variety of reactions and thus can relate e.g. photo-nuclear reactions to pion/proton induced reactions as well as neutrino-nucleus reactions (as addressed here).

In this work we employ the CBUU [1] approach [28] which is based on a set of transport equations for the phase-space distributions $f_h(x,p)$ of hadron h that are coupled via collision terms describing the mutual interaction (or decay and formation) rates in phase space. The mean-fields for the baryons are the same as in Ref. [24] while the description of hadronic collisions is identical to Ref. [10].

For the neutrino-nucleus reactions we employ a perturbative treatment as in the case of photo-nuclear reactions [13] which allows us to obtain good statistics even for weakly interacting probes. In this respect the total neutrino-nucleus reaction is divided into two parts: i) the initial neutrino interaction on a single nucleon of the target (including its local Fermi motion and mean-field potential) and ii) the propagation and decay of the excited resonance (as well as the decay products) in the residual nucleus. Each excited resonance in step i) is assigned a weight W_i proportional to the double differential cross section $d\sigma/d\nu dq^2$ where ν and q^2 are selected by Monte Carlo in the kinematical allowed regime according to the differential distributions displayed e.g. in Fig. 1 for $E_\nu = 1$ GeV. A large number of simulations ($\sim 10^4$) are performed such that the sum over the weights W_i - normalized by the number of events - is equal to the ν and q^2 integrated cross section per nucleon. Note that for fixed ν and q^2 and each individual 4-momentum q_N of the nucleon the invariant energy as well as the 3-momentum of the excited resonance are fully determined by the energy and momentum conservation.

We then follow the motion of the perturbative hadrons (here Δ's, decay pions and nucleons) within the full background of residual nucleons by propagating the Δ's with 2/3 of the nucleon potential - neglecting pion potentials in this study - and compute their collisional history with the residual nucleons of the target. A reduced Δ potential - relative to the nucleon potential - is adopted in order to improve the description of pion spectra from p+A reactions and to incorporate the findings from Peters *et al.* [29] for coherent photo-production of pions on nuclei. In order to trace back the FSI of the hadrons the Δ-production vertices are recorded with their individual weight (including their 4-momenta) as well as the 4-momenta of the final pions.

We point out that an alternative transport description of neutrino-nucleus reactions on the basis of the GiBUU transport model has been initiated by T. Leitner *et al.*

[1] Coupled-Channel Boltzmann-Uehling-Uhlenbeck

in Refs. [30].

Here we present the calculated cross sections for π^+ meson production in CC reactions on ^{12}C targets. The results are displayed in Fig. 3 for the two parameter sets discussed in the context of the elementary cross sections shown in Fig. 2. We find that the parameter set A underestimates the preliminary data on ^{12}C from Ref. [31] as in case of the proton or neutron target in Fig. 2 while the parameter set B performs better (as expected from Fig. 2). Note, however, that any agreement/disagreement is primarily due to the 'uncertain' axial-vector form factor $G^A(q^2)$ such that no final conclusions can be drawn from the comparison in Fig. 3.

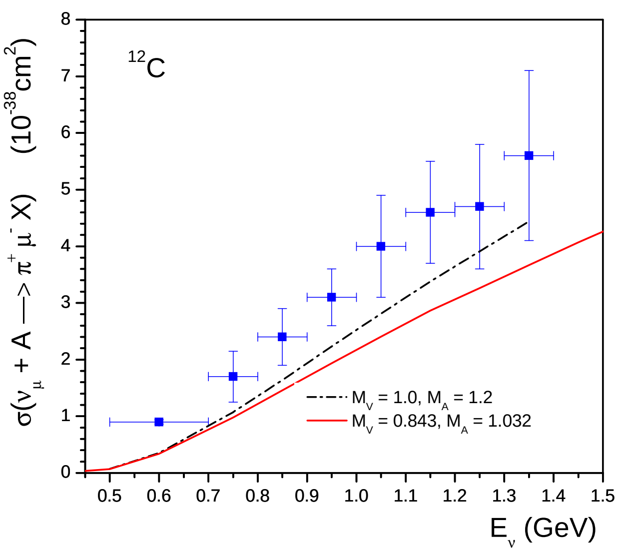

Fig. 3. The total cross section σ_{π^+} for the reaction $\nu + ^{12}C \to \mu^- + \pi^+ + X$ as a function of the neutrino energy E_ν for the two parameter sets discussed in the text. The preliminary data have been taken from Ref. [31].

As an example the differential pion (π^+, π^0) spectra in the pion kinetic energy T_π - divided by the pion laboratory momentum P_{lab} squared - are shown in Fig. 4 for a ^{12}C and ^{56}Fe target at the neutrino energy $E_\nu = 1$ GeV. The differential spectra $d\sigma_\pi/dT_\pi/P^2_{lab}$ for ^{12}C and ^{56}Fe show a shoulder at low T_π and are roughly exponential for high pion energies. The shape of the spectra is similar for both targets but they do not simply scale by a factor of $36/8 = 4.5$ as expected from a scaling of the elementary cross sections. (This factor comes about as follows: (26+30/3)/(6+6/3) when counting the protons and neutrons with their excitation to Δ^{++} and Δ^+, respectively, and the relative decay to π^+. For π^0 the decay fraction of the Δ^+ is 2/3, however, no direct π^0's can be produced in CC reactions on protons. The corresponding scaling factor thus is 30/6= 5.) In case of the Fe target we also display the π^- spectra (upper part) that are down by an order of magnitude relative to the π^+ spectra and stronger localized at low pion energies. Note that no direct negative pions can be produced in the CC neutrino reactions on nucleons and therefore the final π^- (or π^-/π^+ ratio) provide a sensitive probe for the strength of the FSI.

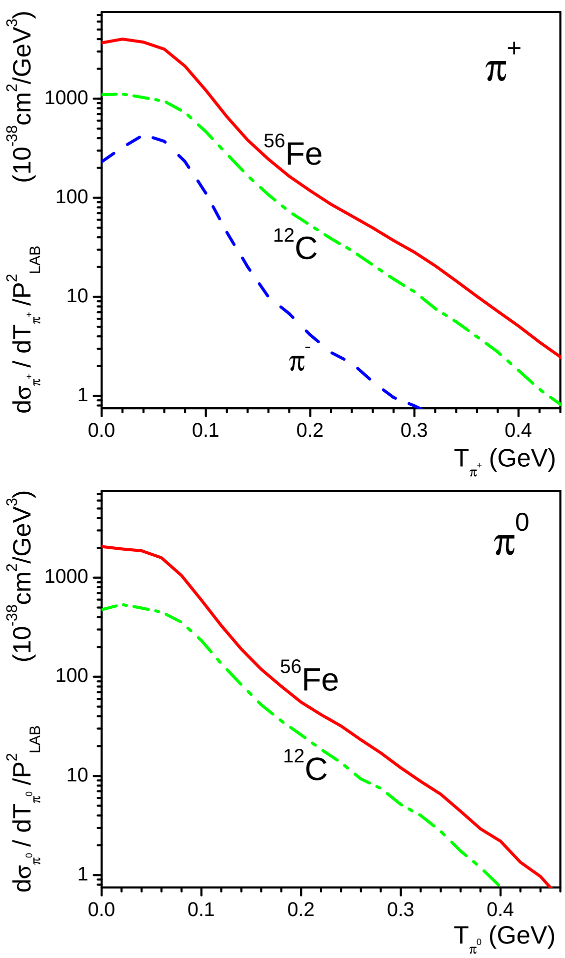

Fig. 4. The differential cross sections $d\sigma_{\pi^+}/dT_\pi/P^2_{lab}$ (upper part) and $d\sigma_{\pi^0}/dT_\pi/P^2_{lab}$ (lower part) for the reactions $\nu +^{12} C((^{56}Fe) \to \mu^- + \pi + X$ as a function of the pion kinetic energy T_π in the laboratory for a neutrino energy $E_\nu = 1$ GeV. The π^- differential spectrum (in case of the ^{56}Fe target) is shown by the dashed line (in the upper part) and is entirely due to final state interactions in the target nucleus.

Since the differential pion spectra suffer from the same uncertainties as the integrated spectra we turn to ratios of cross sections that reflect dominantly the influence of the FSI. For this purpose we consider the ratios

$$R_x(\mathbf{p}) = \frac{(d^3\sigma_x/d^3p)_{fin}}{(d^3\sigma_x/d^3p)_{in}} \tag{16}$$

where the initial differential spectra in the denominator of Eq. (16) are determined from the decay of the primarily produced Δ resonances without FSI. Fig. 5 shows the ratio R_0 of the final differential π^0 momentum spectrum to the neutral pion spectrum without FSI for $\nu_\mu +^{56} Fe$ at $E_\nu = 1$ GeV as a function of the longitudinal momentum P_z and transverse momentum P_T (with respect to the direction of the incoming neutrino). This ratio is roughly constant ($R \sim 0.4$) for $\sqrt{P_T^2 + P_z^2} > 0.2$ GeV/c and exceeds unity for lower pion momenta in the laboratory due to strong FSI of the Δ's and decaying pions with nucleons. We recall that $N\Delta$ interactions in the medium involve - apart from energy and momentum exchange – charge transfer as well as $\Delta N \to NN$ absorption reactions. The latter cross sections are obtained from refined detailed balance relations that incorporate the finite (mass dependent) width of the Δ-resonance [28]. The strong reduction of the pion spectrum at higher pion momenta is essentially due to $\pi + N \to \Delta$ resonant scattering.

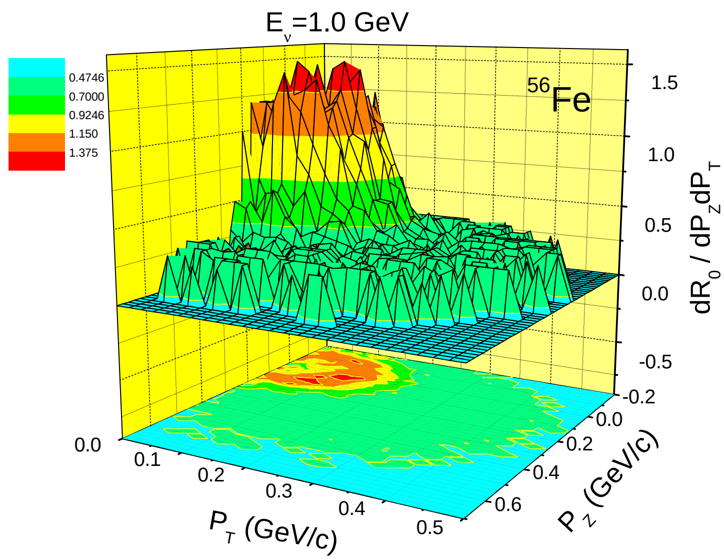

Fig. 5. The ratio R_0 of the final differential π^0 momentum spectrum to the π^0 spectrum without FSI for $\nu_\mu +^{56} Fe$ at $E_\nu = 1$ GeV as a function of the longitudinal momentum P_z and transverse momentum P_T (with respect to the direction of the incoming neutrino).

Apart from the overview in Fig. 5 it is, furthermore, of interest to quantify the strength of the FSI e.g. as a function of the pion kinetic energy in the laboratory T_π. All ratios displayed in Fig. 6 for π^+ (upper part) and π^0 (lower part) show a characteristic dip at low kinetic energy T_π followed by a bump (with a ratio above unity due to pion rescattering) and an approximate plateau for $T_\pi > 0.15$ GeV which is lower for the heavier Fe-target than for the light C-nucleus. These differential FSI effects can also be directly assessed by taking experimental differential ratios of spectra for heavy and light targets.

Note that charged current reactions with pion production and subsequent absorption of the pion might be misinterpreted experimentally as the quasi-elastic CC reactions and lead to an overestimation of the CC quasi-elastic cross sections. In case of the ^{12}C target we find an integrated π^+ (π^0) absorption of 12% (14%). When imposing a detection threshold for pions of T_π= 100 MeV in the laboratory the relative absorption amounts to 33% (35%) for π^+ (π^0). For the ^{56}Fe target the respective numbers are 35% (42%) for the integrated spectra and 58% (64%) for an energy cut of T_π=100 MeV.

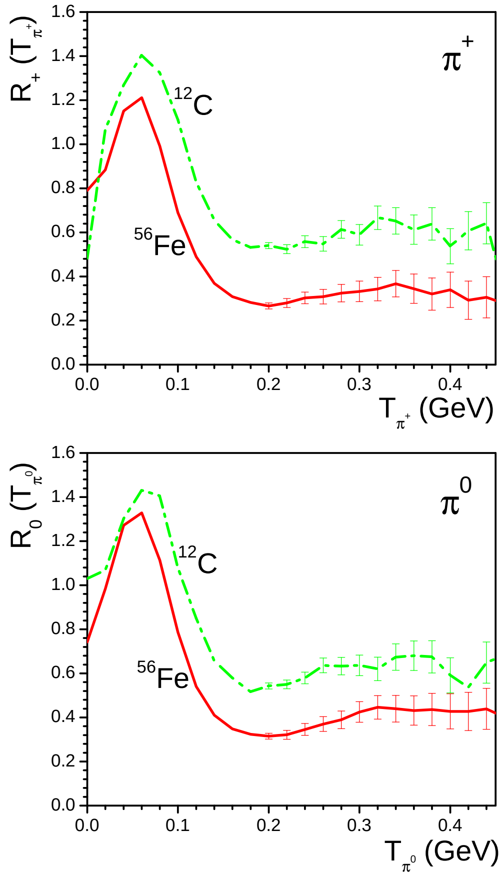

Fig. 6. The differential ratios $R_+(T_\pi)$ (upper part) and $R_0(T_\pi)$ (lower part) for the reactions $\nu_\mu +^{12} C(^{56}Fe) \to \mu^- + \pi^+(\pi^0) + X$ as a function of the pion kinetic energy T_π in the laboratory for a neutrino energy $E_\nu = 1$ GeV. The error bars denote the statistical uncertainty in determining the ratios numerically due to the low cross sections at large pion energies (cf. Fig. 4).

4 Summary

In this study we have reported first dynamical transport calculations for neutrino-nucleus reactions in the energy range from 0.3 - 1.5 GeV. The advantage of our transport description is that it is suited also for a wide variety of reactions and thus can relate neutrino-nucleus reactions to photo-nuclear reactions or pion/proton induced reactions on nuclei. Furthermore, standard in-medium effects such as mean-field potentials or in-medium broadening of hadronic resonances can be exploited within the same framework. Effects of Fermi motion and Pauli-blocking of nucleons are incorporated by default.

The method employed here is quite general and can be applied to a wide variety of nuclei and reaction channels that incorporate all possible final state interactions. Furthermore, the transport approach can be used for an event-by-event analysis and correlate the momenta of different particles in each event, e.g. emitted nucleons with pions *etc.*. It also allows for a clean implementation of experimental acceptance cuts (i.e. detector thresholds and/or detector geometry). Hence, it should be applicable to the description of the neutrino-pion production on nuclei, in particular to the description of the final-state-interactions (FSI) of the produced hadrons.

In our first investigation we have focused on resonant pion production channels via the $\Delta_{33}(1232)$ resonance in charged current (CC) reactions. The final-state-interactions of the resonance as well as the emitted pions have been calculated explicitly for ^{12}C and ^{56}Fe nuclei and show a dominance of pion suppression for pion momenta above 0.2 GeV/c due to Δ absorption on nucleons ($N\Delta \to NN$) as well as strong pion rescattering in the kinematic regime of the Δ resonance excitation. Neutrino reactions on ^{16}O are similar to ^{12}C targets and will be reported elsewhere. A comparison to integrated π^+ spectra for $\nu_\mu +^{12} C$ reactions demonstrates a reasonable agreement in view of the uncertainties in the vector and axial-vector form factors for the elementary reactions on nucleons.

We stress that precise double differential data (with respect to ν and q^2) on free nucleons are mandatory before addressing the FSI in a differential manner as proposed in this study. Once this task is solved the question of in-medium effects on resonance transitions in neutrino-nucleus reactions can be addressed and transition amplitudes to higher baryonic resonances can be investigated. The coupled-channel transport calculations used here already include the various in-medium phenomena and provide a firm basis for the analysis of future differential data.

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